Astrometry of natural satellites Improving the dynamics of planetary systems with old observations

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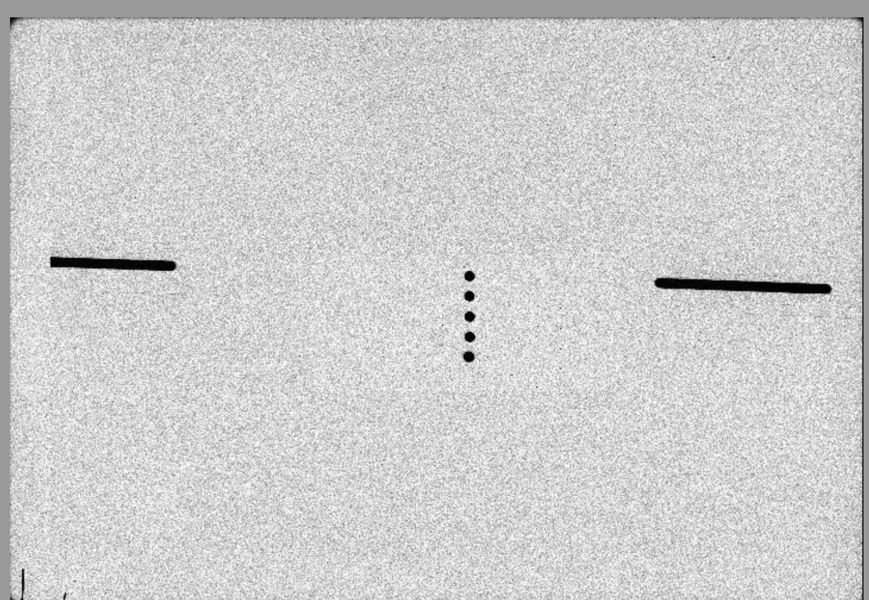
Abstract

A new astrometric reduction of old photographic plates, benefiting from modern technologies such as sub-micrometric scanners associated with a reduction using accurate catalogues (UCAC at the present time and Gaia in a near future), provides improved knowledge of the orbital motion of planetary satellites.
In the framework of an international collaboration first, and in the FP7 ESPaCE european project afterward, U.S. Naval Observatory plates were digitized with the new generation DAMIAN scanning machine of the Royal Observatory of Belgium. The procedure was applied to a few hundred photographic plates of the Galilean satellites covering the years 1967-1998, and of the Martian satellites covering the years 1967-1997.

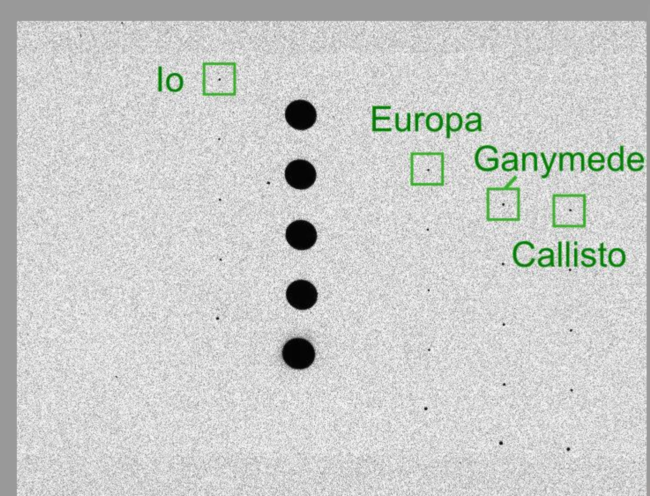
We provide results with an accuracy better than 70 mas in (RA,Dec) positions of the Galilean moons, and better than 60 mas in (RA,Dec) positions of the Martian satellites. Since the positions of Jupiter and Mars may be deduced from the observed (RA,Dec) positions of their satellites, we can also assess the accuracy of the ephemerides of Jupiter and Mars.

ESPaCE FP7 program and USNO photographic plates

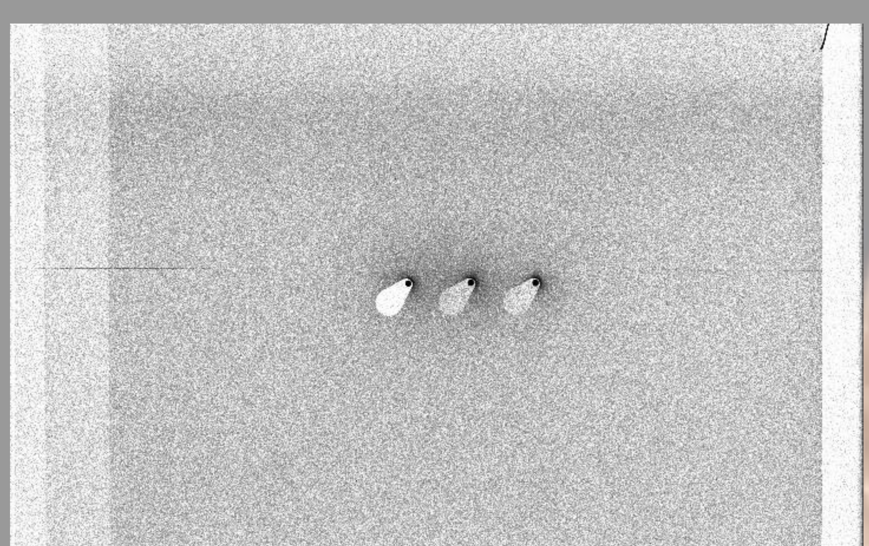
The European Satellites PArtnership for Computing Ephemerides ESPaCE project aims at strengthening the collaboration and at developing new knowledge, new technology, and products for the scientific community in the domains of the development of ephemerides and reference systems for natural satellites and spacecraft. The main European research centers involved in space sciences and dynamics contribute by combining their expertise. Their activities are focused on the extraction and analysis of astrometric data from space measurements not yet applied to the dynamics and to combine them with ground-based astrometric data.
We focus here on a subset of a few hundred photographic plates of the Galilean and Martian satellites, taken with the USNO 61-inch reflector (37' field) and the USNO 26-inch refractor (57' field) by D. Pascu (1977, 1979 & 1994) from 1967 to 1998. Each plate contains several exposures shifted on the Dec axis for the Galileans and on the RA axis for the Martians. All these photographic plates were recently digitized with the new generation DAMIAN digitizer (Robert et al., 2011).



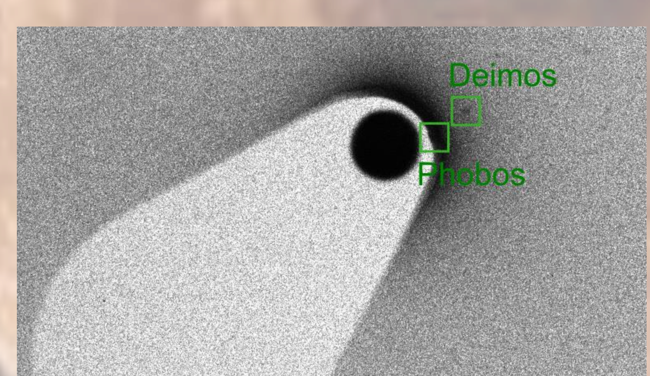
The USNO Galilean plate n°24014



Center of the USNO Galilean plate n°24014



The USNO Martian plate n°11001



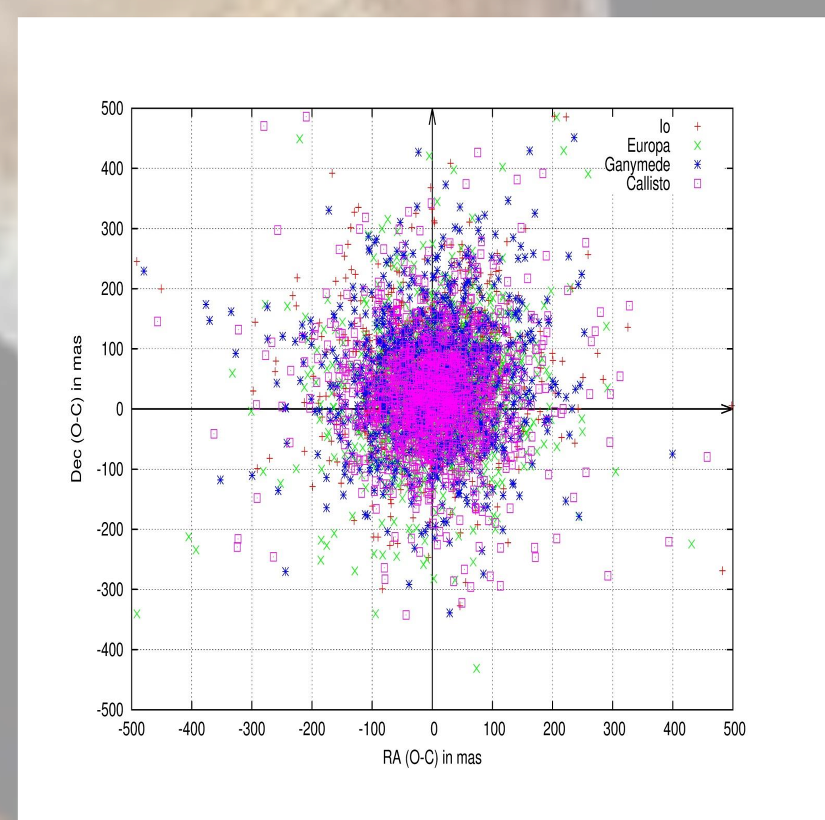
Center of the USNO Martian plate n°11001

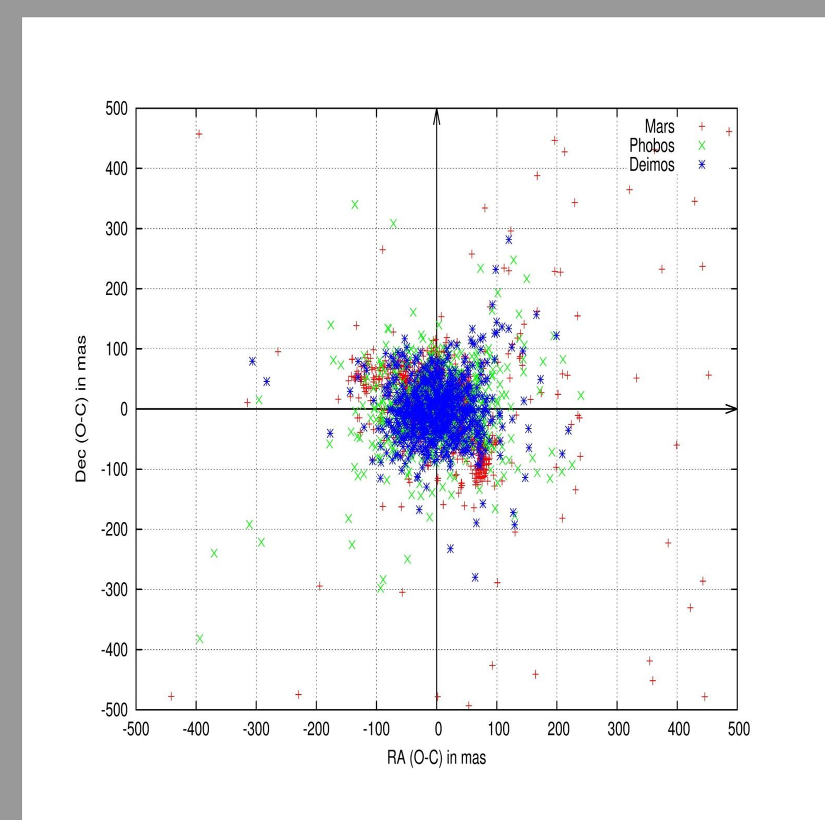
Extraction and identification

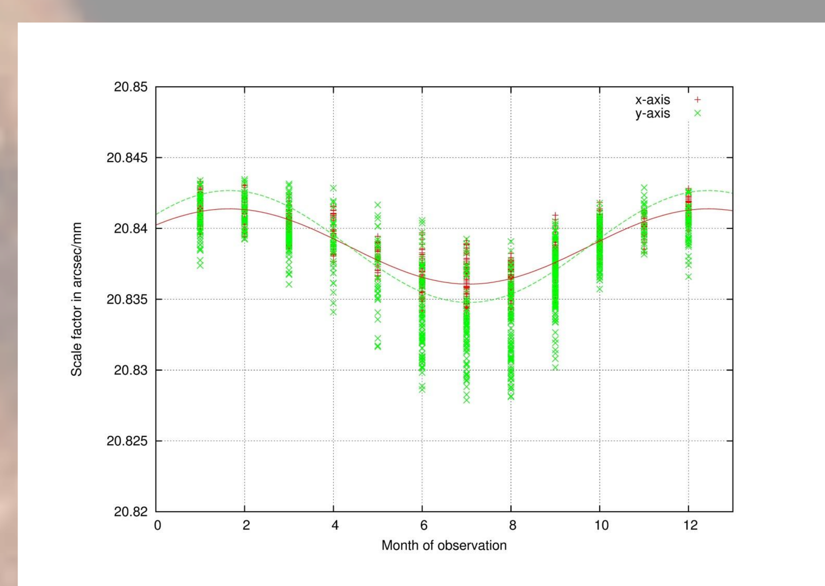
The positions of the images of the planet, satellites and stars are extracted by means of the Source Extractor software (Bertin et al., 1996), used to create a list of objects detected on the plates. A selection for approximately circular objects and FWHM and magnitude constraints permit to reduce the list of possible detected sources. More particular, the positions of the planet Mars are extracted by an IDL ellipse and limb fitting, the positions of the satellites are extracted by an IDL Gaussian fitting after correcting for the background gradient due to the planet's halo.
The objects assumed to be present in the field are identified from existing catalogs to select only real astrometric sources. This process defines areas on the images in which the objects have to be found (Robert, 2011). All the available stars (depending on the catalog used) are identified and more, those that are not detected by eye. We demonstrated that the method can be applied with all planetary systems.
The obtained positions are finally corrected for the optical distortion introduced by the objective/camera unit during the digitization and for the instrumental coma-magnitude effect.

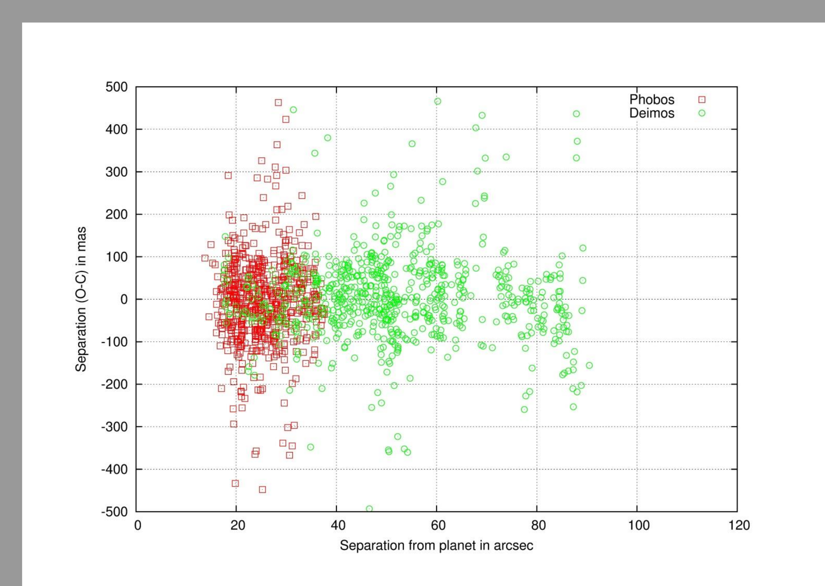
Astrometric reduction

Astrometric (RA,Dec) results of the satellites and the planets are determined in an ICRS geocentric frame to be easily compared with the most recent satellite and planetary ephemerides.
Because of the few number of available stars, the astrometric reduction is quite different from a common astrometric process: the positions are calculated after correcting for instrumental and spherical effects that take into account the parallax and aberration effects and the total atmospheric refraction.
(RA,Dec) positions are deduced from tangential apparent coordinates; only 4 parameters modeling the scale, orientation and center of field are fitted for a minimum of 2 reference stars. The contribution of each effect is separated.









Galilean astrometric results

The (O-C)s are for observations of Io, Europa, Ganymede and Callisto first, and for Mars, Phobos and Deimos following. Positions are deduced from the measurements.
The two first Figures show details of the (RA,Dec) (O-C)s according to the INPOP10 (Fienga et al., 2010) planetary ephemeris and IMCCE (Lainey et al., 2007, 2009) satellite ephemerides. The next Figure shows the contribution of the temperature on the scale variation, while the last Figure indicates that the planetary halo has negligible effect on the satellite positions. Tables compare the averages of the Galilean and Martian (RA,Dec) (O-C)s and rms residuals respectively, in mas, according to the INPOP08 (Fienga et al., 2008), INPOP10, DE421 and DE430 (Folkner et al., 2008, 2014)) planetary ephemerides.

Galilean observations	$\overline{(O-C)}_{\alpha\cos\delta}$	$\overline{\sigma}_{\alpha\cos\delta}$	$\overline{(O-C)}_{\delta}$	$\overline{\sigma}_{\delta}$
INPOP08	42,7	74,3	47,9	94,9
INPOP10	3,1	69,7	34,7	76,4
DE421	-1,3	70,1	39,0	77,6
DE430	-1,8	70,0	37,7	78,0

Martian observations	$\overline{(O-C)}_{\alpha\cos\delta}$	$\overline{\sigma}_{\alpha\cos\delta}$	$\overline{(O-C)}_{\delta}$	$\overline{\sigma}_{\delta}$
INPOP08	2,3	59,8	2,6	57,8
INPOP10	3,2	59,8	2,8	57,8
DE421	2,3	59,7	2,7	57,8
DE430	2,6	59,7	2,7	57,8

Conclusion

We demonstrated the high interest to continue the analysis of old photographic plates such as USNO's. Thanks to the new technologies, we were able to provide astrometric data with a high accuracy after applying the necessary corrections.
We now provide an accuracy about of 70 mas (~210 km) for (RA,Dec) positions of the planet Jupiter and its moons. We also provide an accuracy about of 60 mas (~18 km) for (RA,Dec) positions of the planet Mars and its satellites. Note that the previous accuracy was about of 200 mas and only for relative positions. More important, these results indicate that we now can reach an accuracy better than that of CCD observations (Colas et al., 1991) and as good as the old spacecraft measurements of the Martian system for example. These results encourage us to continue the analysis of old photograhic plates.
We have at the present time a set of several hundred USNO plates of the Saturnian system. The digitization and new reduction are also part of the FP7 European project. The steps after will be to reduce other relevant old photographic plates such as Yale Southern Station Saturnian observations, and to continue the effort in reducing old observations, participating in new programs such as the NAROO project (New Astrometric Reduction of Old Observations) of the IMCCE / Paris Observatory.

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